Satellite remote-sensing technologies used in forest fire management

TIAN Xiao-rui[1*], Douglas J. Mcrae[2], SHU Li-fu[1], WANG Ming-yu[1], LI Hong[1]

[1] *Research Institute of Forestry Protection, Chinese Academy of Forestry. Beijing 100091, P. R. China*

[2]*Natural Resources Canada, Canadian Forest Service, 1219 Queen St. E. Sault Ste. Marie, Ontario P6A 2E5*

Abstract: Satellite remote sensing has become a primary data source for fire danger rating prediction, fuel and fire mapping, fire monitoring, and fire ecology research. This paper summarizes the research achievements in these research fields, and discusses the future trend in the use of satellite remote-sensing techniques in wildfire management. Fuel-type maps from remote-sensing data can now be produced at spatial and temporal scales quite adequate for operational fire management applications. US National Oceanic and Atmospheric Administration (NOAA) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellites are being used for fire detection worldwide due to their high temporal resolution and ability to detect fires in remote regions. Results can be quickly presented on many Websites providing a valuable service readily available to fire agency. As cost-effective tools, satellite remote-sensing techniques play an important role in fire mapping. Improved remote-sensing techniques have the potential to date older fire scars and provide estimates of burn severity. Satellite remote sensing is well suited to assessing the extent of biomass burning, a prerequisite for estimating emissions at regional and global scales, which are needed for better understanding the effects of fire on climate change. The types of satellites used in fire research are also discussed in the paper. Suggestions on what remote-sensing efforts should be completed in China to modernize fire management technology in this country are given.

Key words: Satellite remote sensing; Fire management; Fuel mapping; Fire detection; Review

CLC number: S762 **Document code:** A **Article ID**: 1007-662X(2005)01-0073-06

Introduction

With the development of sensors, remote-sensing techniques, including aerial photography and satellite imagery, are widely used currently in wildfire management. Over the past twenty years, satellite remote sensing has improved and can now provide cost-effective information about the forest for fire management decisions over large landscape areas. Satellite remote sensing has become a major data resource for fire danger rating prediction, fuel and fire mapping, fire monitoring, and fire ecology research. With rising concern over global warming and projected significant impacts of fire on the boreal zone, remote sensing will be critical to the timely monitoring of biomass emissions.

Fuel mapping

The knowledge of natural fuel loads (biomass weights) and species composition is critical for improving current fire prevention and fire behavior modeling programs, which can alleviate the negative effects of fire on the ecosystem. Fuel-type maps are essential for computing fire hazard spatially and for assessing fire risk by their use in models simulating fire growth and intensity across a landscape (Keane *et al.* 2001). Fuel-type maps account for structural characteristics of vegetation related to fire behavior and fire propagation. Fuel conditions refer to the morphological (i.e., biomass, height, density, etc.) and physiological (i.e., moisture status) characteristics of different types of vegetation. Because the description of fuel properties is usually very complex given the vast variety of species often present, fire managers often use fuel classes to described groups of vegetation types having similar fire behavior characteristics. A fuel type has been defined by Merrill and Alexander (1987) as "An identifiable association of fuel elements of distinctive species, form, size, arrangement, and continuity that will exhibit characteristic fire behavior under defined burning conditions." The fire behavior characteristics of individual vegetation species are not necessarily relevant to fire management since the very same species may present completely different fire propagation rates if their fuel loads, densities, vertical continuity, compactness, or surface area to volume ratio characteristics are different, which can occur with maturity (Deeming *et al.* 1978; Andrews 1986).

The temporal documentation of fuel conditions requires enormous field survey efforts to keep fuel-type maps current, thus constraining their operational usefulness if not kept updated. Satellite remote-sensing techniques provide an alternative source of obtaining fuel data, since they provide comprehensive spatial coverage and enough temporal resolution to update fuel maps in a more efficient and timely manner than traditional aerial photography (Oswald *et al.* 1999) or fieldwork. Additionally, satellite sensors provide digital information that can easily be tied into other spatial databases using Geographic Information System (GIS) analysis, which can be imported into running fire behavior and growth models.

Fuel mapping is an extremely difficult and complex process using remote sensing as it requires expertise in image classification, fire behavior, fuel modeling, ecology, and GIS. The use of remote-sensing data in the classification and mapping of vegetation is becoming the primary method for assessing fuels. There are four approaches to mapping fuels: (1) field reconnaissance; (2) direct-mapping methods; (3) indirect-mapping methods; and (4)

Foundation Item: This paper was supported by the National Science Foundation of Beijing (No. 6042025), China NKBRSF Project (No. 2001CB409600) and the fund of Forest Protection Laboratory, State Forestry Administration.

Biography: TIAN Xiao-rui (1971-), Corresponding author, male, Ph. Doctor, associate professor in Research Institute of Forestry Protection, Chinese Academy of Forestry, Beijing100091, P. R. China.

E-mail: tianxr@forestry.ac.cn

Received date: 2004-11-29

Responsible editor: Chai Ruihai

gradient modeling. Bobbe *et al.* (2001) have described key steps in preparing vegetation maps and summarized the use of digital remotely-sensed data for vegetation mapping. Kwasny (2000) used Landsat 7 Thematic Mapper (TM) images (30-m pixel resolution) and some high-resolution imagery (1-m pixel resolution) to map vegetation in green swamp preserve for fuel modeling purposes. The results have been used for data input into the FARSITE fire growth model which aids fire managers in predicting the intensity and extent of a prescribed burn (Finney *et al.* 1994).

More common has been the generation of fuel maps from remote-sensing images has been based on the analysis of medium-resolution (1.1 km, i.e. NOAA) to high-resolution (60–0.61m, QUICK BIRD, IKONOS, LANDSAT, SPOTV) sensors, such as Landsat MSS and Landsat TM data (Kourtz 1977; Dixon *et al.* 1984; Yool *et al.* 1984; Agee and Pickford 1985; Castro and Chuvieco 1998). Landsat characteristics represent a good compromise between spectral and temporal resolutions with an adequate spatial coverage for normal operational fire management applications (Riaño *et al.* 2002). Fuel-type maps were derived from Landsat TM satellite images and digital elevation data (DEM). The main problem in discriminating amongst fuel types on maps is differences in vegetation height and composition of the understory layer. An estimation of canopy height would help to identify some fuel types. SPOT-HRV has been used to estimate heights using empirical approaches (Wulf *et al.* 1990).

Fuel loads in forested areas are dependent on vegetation type and the re-establishment time since the last fire. Brandis and Jacobson (2003) made a study on the feasibility of using remote-sensing data to estimate vegetative fuel loads. Two methods using Landsat TM data for estimating fuel loads were based on equations developed describing litter accumulation and decomposition. The first method uses classification techniques to predict vegetation types coupled with fire history data to derive current fuel loads. The second method applies a canopy turnover rate to estimate litterfall and subsequently accumulated litter from biomass, thus utilizing the dominant influence of canopy on remote-sensing data. This later method has the potential for estimating fuel quantities that would provide useful spatial information to fire managers.

Other efforts have concentrated on low-spatial resolution sensors, such as the United States National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images (Zhu and Evans 1994). The main advantage of this sensor is the possibility of having a multitemporal database because of its high temporal coverage. This is very useful for characterizing the fuel types at regional and global scales. However, the low spatial resolution of this sensor (1 km at nadir) limits its suitability on stand scales. The classification accuracy of fuel-type discrimination may be rather low when the fuel beds or land-use patterns are very complex.

New sensors, such as hyperspectral and radar have been also tested for this application. For instance, the Airborne Visible/Infrared Imaging Spectrometer imager (with 224 bands) has been used for the spectral characterization of fuel types (Roberts *et al.* 1997). While sensors of this type have great potential for mapping vegetation properties because of their high spectral resolution, they have been limited by the reduced spatial coverage they provide. New satellite hyperspectral sensors, such as Hyperion (http://eo1.gsfc.nasa.gov) and Moderate Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov) may change this situation in the near future.

Fire danger assessment

Forest fire risk indicators have been used by many agencies in charge of forest fire prevention and suppression for a considerable long time. The severity of the risk is commonly estimated by identifying those variables that potentially affect fire initiation and integrating them into an index (FAO 1986). Most work on the assessment of forest fire risk has relied on the use of either meteorological data (Viegas *et al.* 2000) or vegetation indices. Some studies used only remote-sensing data (Paltridge and Barber 1988; Lopez *et al.* 1991; Illera *et al.* 1996), while others used remote-sensing data in conjunction with ground measured meteorological data to estimate evapotranspiration rates (Vidal *et al.* 1994), which were then used as fire risk indices.

Chuvieco *et al.* (2002) defined indices based on reflectance measurements performed by the Landsat TM sensor for estimating moisture content of live Mediterranean fuels for fire danger estimation. Images were processed and correlated with fuel moisture content (FMC) of several grassland and shrubland species. Raw bands were converted to reflectances, and several indices potentially related to water content were calculated from them. Those indices based on the short wave infrared bands (SWIR: 1.4–2.5 mm) and on the contrast between this band and the near infrared band offered the best estimations. For grassland, the integration of visible and SWIR bands provided the highest correlation, which provided significant correlation between reflectances and Normalized Difference Vegetation Indices (NDVIs). For shrub species, indices that include SWIR reflectances performed much better than NDVI because the SWIR band is more sensitive to water absorption. Whereas, NDVI estimates FMC indirectly from the effects of chlorophyll changes due to water content variation and leaf area index (LAI). Lopez *et al.* (2002) combined remote-sensing data with meteorological data for the derivation of a risk index in which the latter accounts for the moisture status of small dead fuels. Burgan *et al.* (1998) made a fire potential index map from data obtained from a fuel model map, a maximum live ratio map, a current relative greenness maps (as calculated from AVHRR/NDVI data), and a reasonably dense network of surface weather stations.

Currently, satellite remote-sensing data are largely used in fire danger forecasting, which serve as an important tool for fire management. For example, bi-weekly (and later weekly) 1-km resolution satellite imagery (AVHRR-derived NDVI data) have been used since 1990s to assess the status of live vegetation through derived variables called "visual greenness" and "relative greenness." The Joint Research Center in Europe also uses the satellite data for the evaluation of forest fire risk for the European region (http://europa.eu.int/comm/environment/civil/prote/cpactiv/cpact06h.htm).

Fire detection

Remote sensing can play an important role in obtaining some information on the occurrence and development of fires. Due to the number of satellite overpasses each day is limited, some fires that ignite between overpasses will be missed to detect timely. Since it is essential to attack wildfires as quickly as possible, this detection delay may result in many fires attaining large sizes under the right burning conditions. This is a current fault with

satellites to detect fires. Although there is a default for detecting forest fires, the satellite is widely used for fire monitoring. Since 1978, AVHRR has flown on NOAA-10 and NOAA-11 polar-orbiting metrological satellites providing imagery required for this application. NOAA-AVHRR imagery has proven the most economical means for measuring distribution of global biomass burning, providing information over large geographical areas (image swath width of more than 3000 km) at medium resolution (1 km at nadir), with twice daily (It is not timely given my comments just above.) sampling frequency. AVHRR provides digital imagery in the visible, near-infrared, and infrared wavelengths of the electro-magnetic spectrum, and has proven particularly useful in delineating burned areas in both forest and savanna (Cahoon *et al.* 1994) ecosystems. AVHRR imagery is provided in five spectral channels. Combining Channels 1, 2, and 4 produces an image that shows forest-fire smoke very well. The thermal infrared channel (Channel 3) provides a smoke-penetrating capability that permits delineation of active flame fronts, making possible mapping of the fire perimeter, even on days when active fires produce large quantities of smoke that obscures the ground. Flannigan and Vonder Haar (1986) and Flannigan (1985) developed the first automated (i.e., non-interactive) set of fire detection criteria. They used both daytime and nighttime data from NOAA-7 to monitor a severe forest fire outbreak in north central Alberta, Canada. A number of case studies have been reported from other regions in the world (Matson *et al.* 1987; Stephens and Matson 1989; Langaas and Muirhead 1988). With time, these studies included an increasingly sophisticated discussion of the limitations and problems associated with fire detection associated with AVHRR. The saturation of the 3.7-μm channel on AVHRR prohibits distinction between small and large fires, and between smoldering and flaming fires. A summary of the main advantages and limitations of the AVHRR technique used can be found in Setzer (1994). Its spatial and temporal resolutions limit AVHRR using in this area. Lee and Tag (1990) presented an alternative approach to non-interactive fire detection. They subjectively chose a threshold fire temperature and used the Dozier model to develop a look-up table specifying which combinations of satellite measurements constituted positive fire detection.

Although AVHRR was originally never built for detecting fires, and as indicated suffers from several drawbacks in this regard, it provides the best data so far in orbital detection of vegetation fires. The need for better tools in assessing biomass burning from remote sensing led to the inclusion of two fire channels in MODIS instrument (Salomonson *et al.* 1989), to be flown on the Earth Observation System (EOS) in 1998 and 2000. In contrast with AVHRR, MODIS is equipped with infrared (IR) spectral channels specifically designed to detect and characterize fires based on emitted thermal energy. MODIS is being done worldwide daily through MODIS Rapid Response System for fire detection (http://rapidfire.sci.gsfc.nasa.gov/production/2002122/). In addition, MODIS data have been used to monitor burn scars, vegetation type and conditions, smoke aerosols, water vapor and clouds for collecting data important for monitoring of the entire fire process and its effects on ecosystems, the atmosphere, and climate. Another series of fixed position satellites GOES 4-7 with VAS instruments have also provided multispectral monitoring of the Western Hemisphere. GOES-8, launched in 1994, increased the temporal (images every 15 minutes in North America and half-hourly elsewhere) and spatial resolution (4 km in the IR bands), thus enabling improved detection of fire characteristics and aerosol loading and transport (Menzel and Prins, 1996; Prins and Menzel, 1996).

The main remote-sensing efforts have been directed towards accurate detection of the presence of fires and their location, which is used to monitor the frequency and spatial distribution of fires. Prins and Menzel (1992, 1994) developed an automated algorithm to detect fires and determine the sub-pixel size of any active fire and the average fire temperature based on an adaptation of the algorithm developed by Dozier (1981). Li *et al.* (2003) developed a modified version of this fire algorithm to improve the detection accuracy significantly, and made an evaluation of AVHRR-based, remote-sensing algorithms for detecting active vegetation fires and mapping burned areas throughout North America. There currently exist dozens of algorithms that are being used to detect and monitor fire activity around the world. To ensure consistency and accuracy, it is important to develop a standard algorithm accepted worldwide. Various AVHRR-based algorithms for detecting active burning can be divided into three general categories: single channel threshold algorithms, multi-channel threshold algorithms, and spatial contextual algorithms (e.g., Li *et al.* 2000). Fire-detection algorithms are generally considered to be reliable compared to algorithms designed to map burned areas. Hot-spot detection algorithms are not robust enough yet for global operational use, and no single sensor algorithm is optimal for generating global fire products.

Fire mapping

Remote-sensing techniques can aid in cost-effective mapping, especially in remote areas and during busy fire seasons. Previous applications of satellite remote sensing for mapping burned forested areas have used sensors from the NOAA-AVHRR and Landsat satellites. For example, Stocks *et al.* (1996) used satellite imagery to map large fire areas in Siberia. NOAA-AVHRR satellite imagery can be analyzed to determine the area growth by using satellite-derived area-estimating techniques (Cahoon *et al.* 1992).

Although older satellites have been used successfully for fire mapping, newer sensors are being designed to enhance vegetation differentiation. The SPOT-VEGETATION (SPOT-VGT) sensor has shown superior potential to AVHRR for differentiating burned areas using the same pixel size. Unlike AVHRR, SPOT-VGT has a short-wave infrared (SWIR) band that is sensitive to changes in vegetation cover (Fraser *et al.* 2000). Fraser and Li (2002) confirmed that using a ratio with SPOT-VGT, similar to the concept of the Normalized Difference Vegetation Index (NDVI), increased the ability to distinguish burn age on the landscape. As vegetation recovers following fire, the SWIR/NIR (Near infrared) ratio will decrease as the SWIR reflectance decreases and the NIR reflectance increases to the pre-fire state. Remmel & Perera (2001) compared three AVHRR/NDVI methods of fire detection and mapping for a case study in northern Ontario, Canada. Fire mapping accuracy was assessed by the spatial coincidence between mapped fires and ground-truthed data using a decision-tree approach and by testing the hypothesis that various calculated accuracy components were equal within an ANOVA design.

Fraser *et al.* (2000) presented a new, hybrid approach for boreal burned area mapping called Hotspot and NDVI Differencing Synergy (HANDS). When employed in conjunction with

NOAA-AVHRR imagery, HANDS provides a consistent means of mapping large burn areas (>10 km^2), whose large sizes are characteristic for boreal fires. Steven *et al.* (2002) used remote-sensing techniques to map and classify the 2000 Cerro Grande/Los Alamos wildfire. They applied a machine-learning technique and implemented a software package called GENIE to the classification of forest fire burn severity using Landsat 7 ETM+ multispectral imagery. Precision images from the European Remote Sensing (ERS) Satellite 2 Synthetic Aperture Radar (SAR) have been used to map burned areas. Meritxell and San-Miguel-Ayanz (2003) made a comparative study on backscatter returns from multi-temporal Canadian RADARSAT-1 and ERS-2 SAR data on a fire-disturbed region of central Portugal. Ruecker and Siegert (2000) used ERS-2 SAR radar images to identify burn scar and assess fire damage. Effects of fire on radar backscatter were investigated in test areas representing different degrees of fire damage that were visited during ground and air surveys. The degree of accuracy of burn scar and fire damage mapping was assessed using random samples of geocoded photographs and videotapes recorded during five air surveys and block forest inventories in one damaged forest area. Mapping accuracy was assessed to be higher than 90 percent for burn-scar identification, while the accuracy for discriminating different damage classes was less than 70 percent. The high mapping accuracy for burn scar identification allows the assessment of burn areas using standard ERS-2 satellite imagery to become an operational tool.

Fire emission and ecology

Biomass burning is a major source of trace gases and aerosol particles, with significant ramifications for atmospheric chemistry, cloud properties, and radiation budget (Crutzen *et al.* 1979; Crutzen and Andreae 1990; Kaufman *et al.* 1992; Kaufman and Nakajima 1993) and consequently to climate change (Dickinson 1993; Andreae 1995; IPCC 1995; Penner *et al.* 1992). Biomass burning contributes about a quarter of all global emission of greenhouse gases (Andreae & Merlet 2001). Satellite remote sensing is well suited for assessing the area of biomass burning, which is a prerequisite for estimating emissions at regional and global scales. Commonly used satellite-based techniques for measuring burned areas, include thermal hotspot detection and multitemporal NDVI analysis, have certain limitations.

In order to use AVHRR fire detection in regional assessments of emissions from fires, Kaufman *et al.* (1990a, b) used fire and smoke detection data acquired from NOAA-9. In regions where the smoke was clearly identified to originate from specific groups of fires, the average emission of particulates per fire was calculated and used to convert the total seasonal number of fires into an emission estimate. Justice *et al.* (1996) combined AVHRR fire information in a dynamic model to generate improved trace gas and particulate emission estimates for Southern Africa. The approach combined satellite data on fire distribution and timing with fuel load calculated by a simplified ecosystem production model and ground based measurements of emission ratios (Ward *et al.* 1996; Shea *et al.* 1996). Li *et al.* (2000) used NOAA-AVHRR imagery to conduct a comprehensive investigation of Canadian boreal forest fires. Algorithms were developed to map burned areas on a daily and annual basis with the estimated fire emissions based on burned area and the Canadian Forest Service fuel consumption models (Forestry Canada Fire Danger Group 1992). The burn area algorithms lay the foundation for development of an operational fire emissions calculator (Li *et al.* 2000). Lim & Bretschneider (2004) proposed an autonomous fire and haze detection technique using satellite images in the visible and near infrared wavelength range. The proposed algorithm achieves a very high reliability although the utilized camera is not necessarily optimal for this task with respect to its spectral characteristics. As a consequence of the imaging characteristic, the efficiency is not satisfying in all cases of satellite use. However, new generation sensors (e.g., SPOT VGT, Terra MODIS) should help enable its successful application to a wider range of environments and conditions.

Research has also shown that aerosols from fire directly and indirectly affect radiative forcings (Konzelmann *et al.* 1996; Wild 1999), and postfire burn scars alter the albedo, which both further influence the radiation budget (French 2002). Currently, aerosol-cloud interactions are thought to be one of the most important but least understood drivers of climate change. Feedbacks from fire have the potential to influence regional and global climate by altering atmospheric chemistry and the radiation budget.

Wildfire is the dominant disturbance in boreal regions and acts as a catalyst to maintain and alter the mosaic composition of the forest, consequently altering how carbon is stored. Amiro *et al.* (2001) used a novel approach to estimate emissions for Canada using a satellite-based fire database, fuel consumption calculations for each ecozone, time of fire, and prevailing weather. Similarly, Soja *et al.* (2004) used satellite-based area burned products in their research to estimate emissions of CO, CO_2, CH_4, total nonmethane hydrocarbons (TNMHC) and carbonaceous aerosols from Siberian fires.

Understanding natural fire regimes is crucial in the development of harvesting scenarios and for conducting sustainable resource management in the forest. Cost-effective satellite remote sensing can help scientists to collect large quantity of data over vast and isolated landscapes that would be impossible to collect by any other means. Amiro & Chen (2003) used SPOT-VGT to age forest fire scar located across various Canadian ecoregions. The usefulness of SPOT-VGT to age fires in 18 Canadian ecoregions was evaluated for a period up to 50 years since the occurrence of fire. While useful to approximate fire scar ages, the accuracy is limited because of the variation in forest succession across the landscape, and it cannot replace more detailed mapping done currently by fire agencies. Algorithms developed with SPOT-VGT data are expected to be directly applicable to MODIS sensors (250 m for NIR and 500 m for SWIR bands) with similar spectral bands. Improved remote-sensing techniques have the potential to date fire scars and estimate burn severity.

Conclusion

Accurate fuel-type maps provide information for fire managers to carry out prevention, detection, and suppression strategies, such as forest thinning, prescribed burning, and optimum fire tower locations. Two well-known fire behaviour fuel type systems are the US system (Albini 1976) and the Canadian Forest Fire Behaviour Prediction (FBP) System (Lawson *et al.* 1985; Forestry Canada Fire Danger Group 1992). Recently, European researchers developed a new system based on satellite imagery, in the framework of the Prometheus project (http://www.agroselviter.unito.it), which is better adapted to fuels found in Mediterranean ecosystems. China has never estab-

lished its own fuel-type system, which limits the fire management development. We suggest that in the next several years that Chinese researchers should increase their efforts in developing such a system based on the techniques of satellite remote sensing and GIS. Without a fuel-type system, fire behavior models for China cannot be developed. This will require better field data, development of fuel models specific to China, accurate GIS reference layers, improved satellite imagery, and comprehensive ecosystem models.

Since the Daxing'anling conflagration in 1987, satellite remote-sensing techniques have been used for fire detection in China. There are four daily overpasses for two satellites. Currently NOAA and FY_1C (Fengyun meteorological satellite) are used routinely, while MODIS application is still being tested. Rarely is it found in any Chinese fire reports the actual use of satellite imagery to assess burned areas. As a cost-efficient tool, satellite imagines will provide accurate evaluation of the burned areas to build national databases, which is important information for the fire strategy.

Forest fires are not necessarily limited to just local effects. They can be accumulative and contribute to regional and global problems. An aerosol-cloud interaction is one of the most important and uncertain drivers of climate change. Many researchers are involved in the fire and climate change research activities worldwide. China needs to address this need and to increase its future efforts within its own domain. Although we can find some papers on fire emissions in China, these studies are still just a beginning of what is required. A priority should be in conducting fire experiments in China, and remote-sensing data for producing an accurate assessment of the national fire emissions should be explored. While the establishlishment of a national fire danger-rating system must be a Chinese priority, the development of satellite remote-sensing techniques must be pushed for China to ensure the advancement of its fire management program.

References

Agee, J.K., and Pickford, S.G. 1985. Vegetation and fuel mapping of North Cascades National Park [R]. College of Forest Resources, University of Washington, Seattle. Final Report.

Albini, F.A. 1976. Estimating wildfire behavior and effects [R]. USDA For. Serv. Gen. Tech. Rep. INT-30.

Amiro, B., Todd, J., Wotton, B., Logan, K., Flannigan, M., Stocks, B., Mason, J., Martell, D., and Hirsch, K. 2001. Direct carbon emissions from Canadian forest fires, 1959-1999 [J], Can. J. For. Res., **31**: 512- 525.

Amiro, B.D., Chen, J.M. 2003. Forest-fire-scar aging using SPOT-VEGETATION for Canadian ecoregions [J]. Can. J. For. Res., **33**: 1116–1125.

Andreae, M.O. and Merlet, P. 2001. Emission of trace gases and aerosols from biomass burning [J]. Global Biogeochemical Cycles, **15**, (4): 955–966.

Andreae, M.O., Fishman, J., Garstang, M., Goldammer, J.G., Justice, C.O., Levine, J.S., Scholes, R.J., Stocks, B.J. and Thompson, A.M. 1994. Biomass burning in the global environment: first results from the IGAC/BIBEX Field Campaign STARE/TRACE-A/SAFARI-92 [C]. In: Prinn R. (Ed.) Global Atmospheric-Biospheric Chemistry. New York: Plenum Press, pp. 83-101.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system. Burn subsystem. Part 1 [R]. USDA For. Serv. Gen. Tech. Rep. INT-194.

Bobbe, T., Lachowski, H., Maus, P., Greer, J., and Dull, C. 2001. A primer on mapping vegetation using remote sensing [J]. Internat. J. Wildl. Fire **10**: 277–287.

Brandis, K. and Jacobson, C. 2003. Estimation of vegetative fuel loads using Landsat TM imagery in New South Wales, Australia [J]. Internat. J. Wildl. Fire, **12**: 185–194.

Burgan, R.E., Klaver, R.W., and Klaver, J.M. 1998. Fuel Models and Fire Potential from Satellite and Surface Observations [J]. Int. J. Wild. Fire, **8**: 159-170.

Cahoon, D.R., Levine, J.S., Cofer III, W.R., and Stocks, B.J. 1994. The extent of burning in African savannas [J]. Adv. Space Res. **14**: 447–454.

Cahoon, D.R., Stocks, B.J., Levine, J.S., Cofer III, W.R., and Chung, C.C. 1992. Evaluation of a technique for satellite-derived estimation of biomass burning [J]. J. Geophys. Res., **97**(D4): 3805-3814.

Castro, R., and Chuvieco, E. 1998. Modeling forest fire danger from geographic information systems [J]. Geocarto Int. **13**: 15–23.

Chuvieco, E., Riano, D., Aguado, I., and Cocero, D. 2002. Estimation of fuel moisture content from multitemporal analysis of Landsat Thematic Mapper reflectance data: applications in fire danger assessment [J]. Int. J. Remote Sensing, **23**: 2145-2162

Crutzen, P.J. and Andreae, M.O. 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. [J] Science. **250**: 1669-1678.

Crutzen, P.J., Heidt, L.E., Krasnec, J.P., Pollock, W.H., and Seiler, W. 1979. Biomass burning as a source of atmospheric gases: CO, H_2, N_2O, NO, CH_3Cl, and COS [J]. Nature, **282**:253-256.

Deeming, J.E., Burgan, R.E., and Cohen, J.D. 1978. The national fire-danger rating system - 1978 [R]. USDA For. Serv. Gen. Tech. Rep. INT-39.

Dickinson, R.E., 1993. Effect of fires on global radiation budget through aerosol and cloud properties [C]. In: P.J. Crutzen and J.G. Goldammer (eds.) Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires. New York: John Wiley & Sons, pp. 107-122.

Dixon, R., Shipley, R., and Briggs, A. 1984. Landsat — a tool for mapping fuel types in the boreal forest of Manitoba: A pilot study [R]. Manitoba Remote Sensing Center, Fire Management and Communications Section, Canada Centre for Remote Sensing, Winnipeg, Man.

Dozier, J. 1981. A method for satellite identification of surface temperature fields of subpixel resolution [J]. Remote Sens. Environ., **11**: 221-229.

FAO. 1986. Wildland Fire Management Terminology. Forestry Pap. M-99.

Finney, M.A. and Andrews, P.L. 1994. The FARSITE fire area simulator: fire management applications and lessons of summer 1994. *in* Presented at the Interior West Fire Council Meeting and Symposium: Coeur d'Alene, ID, Nov. 1-2, 1994.

Flannigan, M.D. 1985. Forest Fire Monitoring Using the NOAA Satellite Series, M.S. Thesis, Department of Atmospheric Sciences, Colorado State Univ., Fort Collins, CO.

Flannigan, M.D. and Vonder Haar, T.H. 1986. Forest fire monitoring using NOAA satellite AVHRR [J]. Can. J. For. Res., **16**: 975-982.

Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System [R]. Forestry Canada, Ottawa, ON. Information Report ST-X-3.

Fraser, R.H., Li, Z., and Cihlar, J. 2000. Hotspot and NDVI differencing synergy (HANDS): a new technique for burned area mapping over boreal forest [J]. Remote Sens. Environ., **74**: 362–376.

Fraser, R.H., and Li, Z. 2002. Estimating fire related parameters in boreal forest using SPOT VEGETATION [J]. Remote Sens. Environ., **82**: 95-110.

Houghton, J.T., Meira Filhno, L.G., Hoesung, L., Callander, B.A., Haites, E., Harris, N., and Maskell, K. 1995. Climate Change 1994 [R]. Cambridge: IPCC Cambridge University Press,.

Illera, P., Fernandez, A., Calle, A., and Casanova, J.L., 1996. Temporal evolution of the NDVI as an indicator of forest fire danger [J]. Internat. J.Remote Sens., **17**: 1093–1105.

Justice, C.O., Kendall, J.D., Dowry, RR., and Scholes, R.J. 1996. Satellite remote sensing of fires during the SAFARI campaign using NOAA advanced very high resolution radiometer data [J]. J. Geophy. Res., **101**: 23,851.

Kaufman, Y.J., Setzer, A., Ward, D., Tanre, D., Holben, B.N. , Menzel, P., Pereira, M.C., and Rasmussen, R. 1992. Biomass burning airborne and spaceborne experiment in the Amazonas (BASE-A) [J]. J. Geophys. Res., **97**: 14581-14599.

Kaufman, Y.J., Tucker, C.J., and Fung, I. 1990b. Remote Sensing of Biomass Burning in the Tropics [J]. J. Geophv. Res., **95**(D7): 9927-9939.

Kaufman, Y.J. and Nakajima, T. 1993. Effect of Amazon smoke on cloud microphysics and albedo-analysis from satellite imagery [J]. J. Applied Meteorology, **32**: 729–744.

Kaufman, Y.J., Setzer, A., Justice, C., Tucker, C.J., Pereira, M.C., and Fung, I. 1990a. Remote Sensing of Biomass Burning in the Tropics [C]. In: J.G. Goldammer (ed.) Fire in the Tropical Biota: Ecosystem Processes and Global challenges. Berlin: Springer-Verlag, pp. 371–399.

Keane, R.E., Burgan R., and Wagtendonk J.V. 2001. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling [J]. Int. J. Wild. Fire, **10**: 301–319.

Konzelmann, T., Cahoon, D.R., and Whitlock, C. H. 1996. Impact of biomass burning in equatorial Africa on the downward surface shortwave irradiance: Observations versus calculations [J]. J. Geophys. Res., **101**(D17): 2833–2844.

Kourtz, P.H. 1977. An application of Landsat digital technology to forest fire fuel type mapping [C]. In: Proceedings of the 11th International Symposium on Remote Sensing of the Environment, Ann Arbor, Mich. Environmental Research Institute of Michigan, Ann Arbor, Mich., pp. 1111–1115..

Kwasny, J.L. 2000. Mapping vegetation in green swamp preserve for fuel modeling using remote sensing techniques. Nicholas School of the Environment of Duke University Great Britain. Master's thesis.

Langaas, S. and Muirhead, K. 1988. Monitoring bushfires in West Africa by weather satellites. In: The 22nd International Symposium on Remote Sensing of the Environment, October 20-26, Abidjan, Cote d. Ivoire.

Lawson, B.D., Stocks, B.J., Alexander, M.E., and Van Wagner, C.E. 1985. A system for predicting fire in Canadian forests [C]. In: Proceedings of the 8th Conference on Fire and Forest Meteorology, Detroit. Mich. Society of American Foresters, Bethesda, Md.

Lee, T.F. and Tag, P.M. 1990. Improved Detection of Hotspots using the AVHRR 3.7 um Channel [J]. Bull. Amer. Meteorol. Soc., **71**: 1722-1730.

Li, Z., Frsaser, R., Jin, J., Abuelgasim, A.A., Csiszar, I., Gong, P., Pu, R. and Hao, W.. 2003. Evaluation of algorithms for fire detection and mapping across North America from satellite [J]. J. Geophy. Res., **108**(D2): 4076.

Li, Z., Kaufman, Y.J., Ichoku, C., Fraser, R., Trishchenko, A., Giglio, L., Jin, J., and Yu, X. 2000. A review of AVHRR-based active fire detection algorithms: principles, limitations, and recommendations [R]. Canada Cent. Remote Sens., Ottawa, Canada.

Lim, R. and Bretschneider. T. 2004. Autonomous monitoring of fire-related haze from space [C]. In: Proceedings of the International Conference on Imaging Science, Systems, and Technology, pp.101–105.

Lopez, A.S., Ayanz, J.S., and Burgan, R.E. 2002. Integration of satellite sensor data, fuel type maps and meteorological observations for evaluation of forest fire risk at the pan-European scale [J]. Int. J. Remote Sens., **23**: 2713–2719.

Lopez, S., Gonzalez-Alonso, F., Llop, R., and Cuevas, J. M., 1991, An evaluation of the utility of NOAA-AVHRR images for monitoring forest fires risk in Spain. Internat. J. Remote Sens. 12: 1841–1851.

Matson, M. and Holben, B. 1987. Satellite detection of tropical burning in Brazil [J]. Int. J. Remote Sens., **8**: 509-516.

Menzel, W.P. and Prins, E.M. 1996. Monitoring biomass burning with the new generation of geostationary satellites [C]. In: Change, J.S. Levine (Ed.) Biomass Burning and Global. Cambridge MA: The MIT Press.

Meritxell, G., and San-Miguel-Ayanz, J. 2003. Fire scar detection in Central Portugal Using RADARSAT-1 and ERS-2 SAR Data. Available at: http://natural-hazards.jrc.it/documents/fires/2003-publications/igarss-paper.pdf

Merrill, D.F. and Alexander, M.E. 1987. Glossary of forest fire management terms [R]. National Research Council of Canada, Committee for Forest Fire Management, Ottawa, Ont.

Oswald, B.P., Fancher, J.T., Kulhavy, D.L., and Reeves, H.C. 1999. Classifying fuels with aerial photography in East Texas [J]. Int. J. Wildland Fire, **9**: 109–113.

Paltridge, G. W. and Barber, J. 1988. Monitoring grasslands dryness and fire potential in Australia with NOAA/AVHRR data [J]. Remote Sens. Environ., **25**: 381–394.

Penner, J.E., Dickenson R.E., and O.Neill, C.A. 1992. Effects of aerosol from biomass burning on the global radiation budget [J]. Science, **256**: 1432–1434.

Prins, E.M. and Menzel, W.P. 1992. Geostationary satellite detection of biomass burning in South America [J]. Int. T. Remote Sens., **13**: 2783-2799.

Prins, E.M. and Menzel, W.P. 1994. Trends in South American biomass burning detected with the GOES visible infrared spin scan radiometer atmospheric sounder from 1983 to 1991 [J]. J. Geoph. Res., **99**: 16719–16735.

Prins, E.M. and Menzel, W.P. 1996. Investigation of biomass burning and aerosol loading and transport utilizing geostationary satellite data [C]. In: J.S. Levine (Ed.) Biomass Burning and Global Change. Cambridge MA: The MIT Press.

Remmel, T.K. and Perera, A.H. 2001. Fire mapping in a northern boreal forest: assessing AVHRR/NDVI methods of change detection [M]. Forest Ecology and Management, **152**: 119–129.

Riaño, D., Chuvieco, E., Salas, J., Orueta, A.P., and Bastarrika, A. 2002. Generation of fuel type maps from Landsat TM images and ancillary data in Mediterranean ecosystems [J]. Can. J. For. Res., **32**: 1301–1315.

Roberts, D.A., Green, R.O., and Adams, J.B. 1997. Temporal and spatial patterns in vegetation and atmospheric properties from AVIRIS [J]. Remote Sens. Environ., **62**: 223–240.

Ruecker, G. and Siegert, F. 2000. Burn scar mapping and fire damage assessment using ERS-2 Sar images in East Kalimantan, Indonesia [R]. IAPRS, Vol. XXXIII, Amsterdam, 1–8.

Salomonson, V.V., Barnes, W.L., Maymon, P.W., Montgomery, H.E., and Ostrow, H. 1989. MODIS: Advanced Facility Instrument for Studies of the Earth as a System [J]. IEEE Trans. on Geosci. and Remote Sens., **27**: 145-153.

Setzer, A.W., and Verstraete, M.M. 1994. Fire and glint in AVHRR Channel 3: A possible reason for the non-saturation mystery [J]. Int. J. of Remote Sens., **15:** 711–718.

Soja, A. J., Cofer, W.R., Shugart, H.H., Sukhinin, A.I., Stackhouse Jr., P.W., McRae, D.J., and Conard, S.G. 2004. Estimating fire emissions and disparities in boreal Siberia (1998–2002) [J]. J. Geophys. Res., **109**: D14S06.

Stephens, G. and Matson, M.. 1989. Fire Detection Using the NOAA-N Satellites [C]. In: Proceedings of the 10th Conference on Fire and Forest Meteorology,, April 17-21, Ottawa, Canada.

Steven, P. B., Koch, S.W., and Hansen, L.A. 2002. Evolutionary computation and post-wildfire land-cover mapping with multispectral imagery. Available at: http://www.genie.lanl.gov/green/publications/brumbySPIE4545.pdf

Stocks, B.J., Lee, B.S., and Martell, D.L. 1996. Some potential carbon budget implications of fire management in the boreal forest [C]. pp. 89-96 In: M.J. Apps and D.T. Price (Eds.) Forest Ecosystems, Forest Management, and the Global Carbon Cycle. NATO ASI Series. Berlin: Springer-Verlag,.

Vidal, A., Pinglo, F., Durand, H., Devaux-Ros, C., and Maillet, A. 1994. Evaluation of temporal fire risk index in the Mediterranean forest from NOAA thermal IR [J]. Remote Sens. Environ., **49**: 296–303.

Viegas, X., Bovio, G., Ferreira, A., Nosenzo, A., and Sol, B. 2000. Comparative study of various methods of fire danger evaluation in southern Europe [J]. Internat. J. Wildl. Fire, **9**: 235–246.

Wild, M. 1999. Discrepancies between model-calculated and observed shortwave atmospheric absorption in areas with high aerosol loadings [J]. J. Geophys. Res., **104:** 27,361–27,371.

Wulf, D.E., Goossens, R.E., Deroover, B.P., and Borry, F.C. 1990. Extraction of forest stand parameters from panchromatic and multispectral SPOT-1 data [J]. Int. J. Remote Sens., **11**: 1571–1588.

Zhu, Z., and Evans, D.L. 1994. U.S. forest types and predicted percent forest cover from AVHRR data [J]. Photogramm. Eng. Remote Sens. **60**: 525–531.